# A New Raman Water Vapor Lidar Calibration Technique and Measurements in the Vicinity of Hurricane Bonnie

Keith D. Evans, Belay B. Demoz, Martin P. Cadirola, S.H. Melfi
*Joint Center for Earth Systems Technology, University of Maryland Baltimore County, Baltimore, MD 21250 USA*

David N. Whiteman
*NASA/Goddard Space Flight Center, Laboratory for Terrestrial Physics, Greenbelt, MD 20771 USA*

Geary K. Schwemmer, David O'C. Starr
*NASA/Goddard Space Flight Center, Laboratory for Atmospheres, Greenbelt, MD 20771 USA*

F. J. Schmidlin
*NASA/GSFC Wallops Flight Facility, Observational Sciences Branch, Wallops, VA USA*

Wayne Feltz and David Tobin
*Space Science and Engineering Center, University of Wisconsin, Madison, WI USA*

Seth I. Gutman
*National Oceanic and Atmospheric Administration, Forecast Systems Laboratory, Boulder, CO 80303 USA*

ABSTRACT

The NASA/Goddard Space Flight Center Scanning Raman Lidar has made measurements of water vapor and aerosols for almost ten years. Calibration of the water vapor data has typically been performed by comparison with another water vapor sensor such as radiosondes. We present a new method for water vapor calibration that only requires low clouds, and surface pressure and temperature measurements. A sensitivity study was performed and the cloud base algorithm agrees with the radiosonde calibration to within 10-15%. Knowledge of the true atmospheric lapse rate is required to obtain more accurate cloud base temperatures. Analysis of water vapor and aerosol measurements made in the vicinity of Hurricane Bonnie are discussed.

# A New Raman Water Vapor Lidar Calibration Technique and Measurements in the Vicinity of Hurricane Bonnie

Keith D. Evans, Belay B. Demoz, Martin P. Cadirola, S.H. Melfi
*Joint Center for Earth Systems Technology, University of Maryland Baltimore County, Baltimore, MD 21250 USA*

David N. Whiteman
*NASA/Goddard Space Flight Center, Laboratory for Terrestrial Physics, Greenbelt, MD 20771 USA*

Geary K. Schwemmer, David O'C. Starr
*NASA/Goddard Space Flight Center, Laboratory for Atmospheres, Greenbelt, MD 20771 USA*

F. J. Schmidlin
*NASA/GSFC Wallops Flight Facility, Observational Sciences Branch, Wallops, VA USA*

Wayne Feltz and David Tobin
*Space Science and Engineering Center, University of Wisconsin, Madison, WI USA*

Seth I. Gutman
*National Oceanic and Atmospheric Administration, Forecast Systems Laboratory, Boulder, CO 80303 USA*

ABSTRACT

The NASA/Goddard Space Flight Center Scanning Raman Lidar has made measurements of water vapor and aerosols for almost ten years. Calibration of the water vapor data has typically been performed by comparison with another water vapor sensor such as radiosondes. We present a new method for water vapor calibration that only requires low clouds, and surface pressure and temperature measurements. A sensitivity study was performed and the cloud base algorithm agrees with the radiosonde calibration to within 10-15%. Knowledge of the true atmospheric lapse rate is required to obtain more accurate cloud base temperatures. Analysis of water vapor and aerosol measurements made in the vicinity of Hurricane Bonnie are discussed.

## 1. Introduction

Water vapor is the most important greenhouse gas in the Earth's atmosphere. Accurate long-term measurements of water vapor are desired to understand the feedback processes of global warming. The NASA/Goddard Space Flight Center Scanning Raman Lidar (SRL)) has been measuring profiles of water vapor for nearly a decade.

Calibrating the SRL water vapor data has frequently been done using an ensemble of radiosonde data (Ferrare *et al.*, 1995). Raman lidars have also been calibrated based on total precipitable water vapor measurements made by a microwave radiometer (Turner *et. al.*, 2000). As an alternative to the technique of calibrating a Raman water vapor lidar with respect to other water vapor instrumentation, we present a new method for calibrating the Raman water vapor data, which uses cloud base as determined by the SRL and surface based measurements. Other than the lidar data, only surface based measurements are used as input to the algorithm. Measurements of water vapor and aerosols in the vicinity of hurricane Bonnie will be presented using the new calibration.

## 2. System Description

Since only nighttime data are presented here, a brief description of the nighttime system follows. Complete system details have recently been published (Whiteman and Melfi, 1999).

The nighttime measurement system uses a XeF excimer laser to transmit light at 351 nm. The system operates at 400 Hz with 30-60 mJ per pulse for average output of 12-24 W in the far field. A 0.76 m, f/5.2, variable field-of-view Dall-Kirkham telescope gathers backscattering from the laser return and the vibrational Raman-shifted returns from $O_2$ (371.5 nm), $N_2$ (382.5 nm), and water vapor (402.8 nm). The telescope is aligned with an elliptical flat mirror (1.2 m x 0.8 m) to enable horizon-to-horizon scanning. Beam splitters separate the return beam into low- and high-sensitivity channels for each wavelength to extend the range of the measurements. The data are typically saved in the form of 1-minute contiguous files with an altitude resolution of 75 m.

The low- and high-sensitivity channels for each wavelength are merged over a range where both channels are giving good data. To obtain the aerosol scattering ratio, the ratio of the merged aerosol (elastic return) and nitrogen profiles is first corrected for spectral differential transmission through the atmosphere (Whiteman *et al.*, 1992). Following this, the ratio is normalized to unity in a cloud-free region of the atmosphere between 6-10 km. The ratio of the water vapor and nitrogen signals must also be corrected for differential transmission before obtaining the water vapor mixing ratio calibration constant. That procedure will now be considered.

### 3. Calibration During CAMEX-3

In August and September 1998, the SRL was on site at Andros Island, Bahamas, as part of the validation/calibration ground-site for the third Convention and Moisture Experiment (CAMEX-3). The intent of CAMEX-3 was to acquire an extensive data set in and around hurricanes to improve hurricane tracking and intensification modeling. While at Andros Island, several hurricanes passed nearby influencing the SRL measurements of water vapor.

Several methods have been used to calibrate the SRL water vapor profiles, such as from first principles (Sherlock *et al.*, 1999) and by comparison with the water vapor mixing ratio or precipitable water vapor measurements from other instruments (Turner *et al.*, 2000).

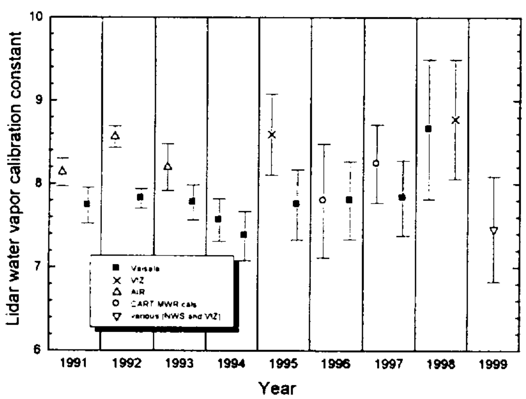


Figure 1 The SRL calibration constant using various radiosondes from 1991-1999.

Because of wide availability and relative ease of use, radiosondes are often used to provide this calibration (Ferrare *et al.*, 1995). To avoid errors from day-to-day variability, faulty data, etc., an ensemble of coincident lidar-radiosonde comparisons are used to obtain the calibration constant. The SRL calibration constant with respect to radiosondes has been tracked over the years and, as can be seen in figure 1, this constant has been relatively stable over the past nine years. Note that the calibration due to Vaisala radiosondes has changed by only 6% peak-to-peak from 1991-1997. Thus, despite the variations that can exist from batch to batch among radiosondes, it seems apparent from this figure that with a sufficiently large number of radiosondes, a stable constant can be obtained. There were several system modifications between 1997 and 1998 (see Cadirola *et al.*, 1999) which could account for the approximately 15% increase in calibration constant in 1998.

Nonetheless, a technique for calibrating the water vapor Raman lidar which does not rely on the measurements of another sensor is an attractive objective. We present below a technique that uses only surface based measurements of pressure and temperature.

### 4. Calibration Using Clouds

Computing a lidar calibration with clouds, requires a measure of the water vapor mixing ratio at the base of the cloud. This can be obtained if one knows the pressure and temperature at cloud base. The pressure at cloud base can be derived from ground measurements using the hypsometric equation. Likewise, the cloud base temperature can be derived from ground measurements using a dry adiabatic lapse rate (9.8° C/km). Since cloud base is defined as the point where the air is saturated, the derived cloud base temperature is converted into water vapor mixing ratio using the Clausius-Clapeyron equation.

For a sensitivity analysis, a range of temperatures was used for the Clausius-Clapeyron equation since it is nonlinear. At 16°C, ±1° resulted in ±1.2 hPa vapor pressure, which amounts to about ±0.9 g/kg over the pressures used (850-930 hPa). At 23°, ±1° resulted in ±1.7 hPa vapor pressure, which amounts to ±1.2 g/kg over the same pressures. The sensitivity of converting the vapor pressures to g/kg was 0.2 g/kg for pressure changes of ±10hPa. These results indicate that the technique is more sensitive to errors in temperature than in pressure.

Cloud base was obtained from the peak in the low aerosol data in the first two kilometers (Eberhard, 1986). In cases where a double peak was found, then the lower peak was taken as cloud base. Data were screened for rain or virga occurrences, for the technique is not applicable in such conditions.

The 10 m radiosonde data were used to test the sensitivity of this method. Only radiosondes through or near clouds and lidar data within ±10 minutes of radiosonde launch time were used for this study. To maintain the validity of the well mixed boundary layer assumption, only data with cloud base at or below 1.05 km were utilized. The difference between the derived and radiosonde pressures at cloud base was 9.43±0.87 hPa and the difference in the temperatures at cloud base was -2.05±1.33° C. This led to a difference in the water vapor mixing ratios of -1.49±1.00 g/kg.

The true value of this algorithm is that one only needs surface measurements of pressure and temperature to utilize it. Using this new cloud-base calibration technique, we obtain calibration values within 10-15% of the calibration value using radiosonde comparisons. This large difference in calibrations is due to the difference in cloud base temperatures. As mentioned above, using the dry adiabatic lapse rate gave a cloud base temperature difference of 2° C, which could lead to a difference in the mixing ratios of 2 g/kg. For water vapor mixing ratios at cloud base in a subtropical air mass (approx. 13-20 g/kg), 2 g/kg amounts to a 10-15% difference.

Knowledge of the true atmospheric lapse rate is required to utilize this cloud calibration algorithm. The radiosonde data show a lapse rate of 7-7.5° C/km, significantly different from dry adiabatic. The difference in lapse rates could be due to the high relative humidities in the subtropical air at Andros. Lapse rates in warm humid air masses could be as low as 4° C/km (Holton 1992, p. 290).

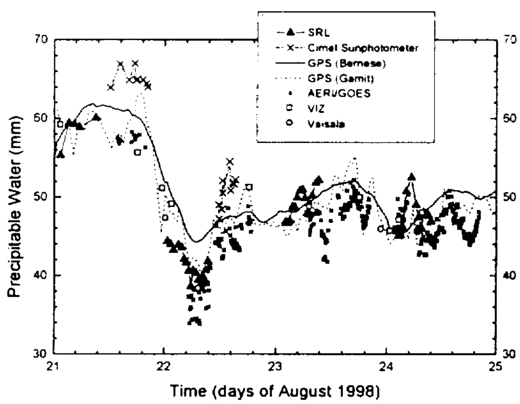


Figure 2. A comparison of precipitable water vapor for the period of Aug. 21-24, 1998, before and during the passage of Hurricane Bonnie.

Upon derivation of the lidar calibration constant, the data are calibrated and can then be analyzed meteorologically. A sample analysis is presented in the next section.

**5. Hurricane Bonnie Passage**

While the SRL was deployed at Andros Island, Bahamas during CAMEX-3, several hurricanes, including Bonnie, influenced the weather on Andros. Hurricane Bonnie's closest approach to Andros Island occurred on August 24, 1998 at 2300 UTC. Fig. 2 is a precipitable water vapor (PWV) comparison for Aug 21-24 for various instruments at Andros Island, including Vaisala and VIZ radiosondes, two methods of PWV computation from GPS (Bernese and Gamit), Cimel sunphotometer, AERI/GOES (Atmospheric Emitted Radiance Instrument, combined with GOES profiles), and the SRL. By computing the SRL PWV in layers (0-1, 1-2, 2-3, 3-4, 4-5 and 5-8 km), it can be shown that the PWV in the lower 2 kms did not change much. Most of the drying occurred in the 3-5 km region of the middle troposphere. This drying would be due to hurricane outflow and subsequent subsidence.

Another feature of hurricanes that was measured by the SRL was cirrus cloud outflow. The thin dark band starting at 0500 above the thick dark band in figure 3, is cirrus cloud outflow from Hurricane Bonnie. These cirrus outflow clouds were at altitudes as high as 16-17 km. This altitude was higher than non-hurricane cirrus clouds that were measured before and after hurricane passage. Radiosonde temperatures show the height of the tropopause increasing as the hurricane approaches, probably due to the deep convection near the eye. Closer to the eye, the clouds would probably be higher leading to troposphere-stratosphere exchange.

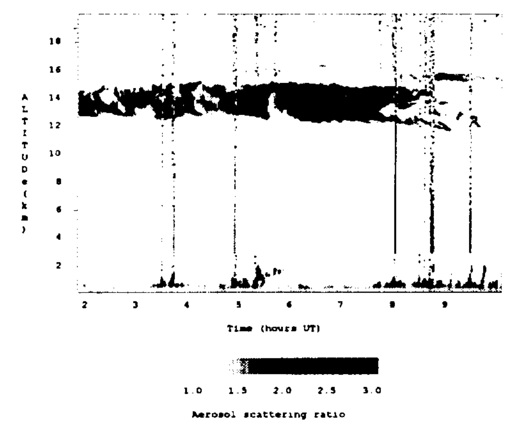


Figure. 3. Image of aerosol scattering ratio from 8/23/98 at Andros Island. The thin band of cirrus above the dark band, starting at 0500 UTC is hurricane outflow.

**6. Conclusions**

We have presented here a method for lidar water vapor calibration that uses only ground temperature and pressure as an alternative to calibration with respect to other water vapor sensors. This method is more sensitive to a proper derivation of cloud base temperature than to cloud base pressure. The SRL calibration obtained using the cloud base algorithm was within 10-15% of the calibration obtained from radiosondes. Knowledge of the true atmospheric lapse rate would improve the cloud base temperature derivation.

We also discussed measurements in the vicinity of Hurricane Bonnie. These measurements show mid-tropospheric drying due to outflow subsidence and cirrus clouds that are at the level of the tropopause due to the deep convection of the hurricane.

## REFERENCES


Cadirola, M.P., D.N. Whiteman, S.H. Melfi, K.D. Evans, B. Demoz, G.Schwemmer, J. Freemire, A.D. Wooten, and S. Wise, Measurement Improvements in the NASA Goddard Space Flight Center's Scanning Raman Lidar, *1999 Optical Remote Sensing of the Atmosphere Conference*, June 1999, 106 (1999).

Eberhard, W.L., Cloud signals from lidar and rotating beam ceilometer compared with pilot ceiling, *J. Atmos. Oceanic Tech.*, **3**, 488-512 (1986).

Ferrare, R.A., D.N. Whiteman, S.H. Melfi, K.D. Evans, F.J. Schmidlin, and D. O'C. Starr, "A Comparison of Water Vapor Measurements made by Raman Lidar and Radiosondes," *J. of Atmos. and Oceanic Tech.*, **12**, No. 6, 1177-1195 (1995).

Holton, James R., An Introduction to Dynamic Meteorology, third ed., Academic Press, new York, pp. 511 (1992).

Sherlock, V., A. Hauchecorne, J. Lenoble, Methodology for the independent calibration of Raman backscatter water-vapor lidar systems, *Applied Optics*, **38**, 5817-5837 (1999).

Turner, D.D., W.F. Feltz, R.A. Ferrare, Continuous Water Profiles from Operational Ground-based Active and Passive Remote Sensors, *submitted to BAMS*, (2000).

Whiteman, David. N., S.H. Melfi, "Cloud liquid water, mean droplet radius and number density measurements using a Raman lidar", *J. Geophys. Res.*, **104**, No. D24, 31411-31419 (1999).

Whiteman, D.N., S.H. Melfi, R.A. Ferrare, Raman Lidar System for Measurement of Water Vapor and Aerosols in the Earth's Atmosphere, *Applied Optics*, **31**, 3068-3082 (1992).

# NASA Scientific and Technical Document Availability Authorization (DAA)

National Aeronautics and Space Administration

*The DAA approval process applies to all forms of published NASA Scientific and Technical Information (STI), whether disseminated in print or electronically. It is to be initiated by the responsible NASA Project Officer, Technical Monitor, author, or other appropriate NASA official for all presentations, reports, papers, and proceedings that contain NASA STI. Explanations are on the back of this form and are presented in greater detail in NPG 2200.2, "Guidelines for Documentation, Approval, and Dissemination of NASA Scientific and Technical Information."*

☒ Original
☐ Modified

## I. DOCUMENT/PROJECT IDENTIFICATION

| TITLE | AUTHOR(S) |
|---|---|
| A New Raman Water Vapor Lidar Calibration Technique and Measurements in the Vicinity of Hurricane Bonnie | Keith D. Evans, Belay B. Demoz, Martin P. Cadirola and S. H. Melfi |
| ORIGINATING NASA ORGANIZATION<br>NASA Goddard Space Flight Center | PERFORMING ORGANIZATION *(If different)* |

| CONTRACT/GRANT/INTERAGENCY/PROJECT NUMBER(S) | DOCUMENT NUMBER(S) | DOCUMENT DATE |
|---|---|---|
| | | |

*For presentations, documents, or other STI to be externally published (including through electronic media), enter appropriate information on the intended publication such as name, place, and date of conference, periodical, or journal name, or book title and publisher in the next box. These documents must be routed to the NASA Headquarters or Center Export Control Administrator for approval (see Sections III and VIII).* ▶ 20th Int'l Laser Radar Conf., 10-14 July, 2000, Vichy, FRANCE

## II. SECURITY CLASSIFICATION

CHECK ONE *(One of the five boxes denoting Security Classification must be checked.)*

☐ SECRET ☐ SECRET RD ☐ CONFIDENTIAL ☐ CONFIDENTIAL RD ☑ UNCLASSIFIED

## III. AVAILABILITY CATEGORY

☐ ITAR ☐ EAR

Export Controlled Document - USML Category /CCL Export Control Classification Number (ECCN) *(Documents marked in this block must have the concurrence/approval of the NASA Headquarters or Center Export Control Administrator (see Section VIII).)*

☐ TRADE SECRET
☐ SBIR
☐ COPYRIGHTED

Confidential Commercial Document *(check appropriate box at left and indicate below the appropriate limitation and expiration)*:

☐ U.S. Government agencies and U.S. Government agency contractors only
☐ NASA contractors and U.S. Government only
☐ U.S. Government agencies only
☐ NASA personnel and NASA contractors only
☐ NASA personnel only
☐ Available only with the approval of issuing office:
☐ Limited until *(date)*

☑ PUBLICLY AVAILABLE

Publicly available documents must be unclassified, may not be export controlled, may not contain trade secret or confidential commercial data, and should have cleared any applicable patents application process.

## IV. DOCUMENT DISCLOSING AN INVENTION

| THIS DOCUMENT MAY BE RELEASED ON *(date)* | NASA HQ OR CENTER PATENT OR INTELLECTUAL PROPERTY COUNSEL SIGNATURE | DATE |
|---|---|---|
| | | |

## V. BLANKET RELEASE (OPTIONAL)

☐ All documents issued under the following contract/grant/project number may be processed as checked in Sections II and III.

☐ The blanket release authorization granted on *(date)*

☐ is RESCINDED - Future documents must have individual availability authorizations.

☐ is MODIFIED - Limitations for all documents processed in the STI system under the blanket release should be changed to conform to blocks as checked in Sections II and III.

**GSFC STI PUBLIC DISCLOSURE EXPORT CONTROL CHECKLIST**

The Export Control Office requests your assistance in assuring that your proposed disclosure of NASA scientific and technical information (STI) complies with the Export Administration Regulations (EAR, 15 CFR 730-774) and the International Traffic In Arms Regulations (ITAR, 22 CFR 120-130). The NASA Export Control Program requires that every domestic and international presentation/publication of GSFC STI be reviewed through the GSFC Export Control Office in accordance with the NASA Form 1676 NASA Scientific and Technical Document Availability Authorization (DAA) process. Release of NASA information into a public forum may provide countries with interests adverse to the United States with access to NASA technology. Failure to comply with the ITAR regulations and/or the Commerce Department regulations may subject you to fines of up to $1 million and/or up to ten years imprisonment per violation. Completion of this checklist should minimize delays in approving most requests for presentation/publication of NASA STI.

Generally, the export of information pertaining to the design, development, production, manufacture, assembly, operation, repair, testing, maintenance or modification of defense articles, *i.e.*, space flight hardware, ground tracking systems, launch vehicles to include sounding rockets and meteorological rockets, radiation hardened hardware and associated hardware and engineering units for these items are controlled by the State Department under the ITAR. A complete listing of items covered by the ITAR can be accessed at http://gsfc-bluenun.gsfc.nasa.gov/export/regsitar.htm. The export of information with respect to ground based sensors, detectors, high-speed computers, and national security and missile technology items are controlled by the U.S. Commerce Department under the EAR. If the information intended for release falls within the above categories but otherwise fits into one or more of the following exemptions, the information may be released.

**EXEMPTION I**
If your information is already in the public domain **in it's entirety** through a non-NASA medium and/or through NASA release previously approved by the Export Control Office, the information is exempt from further review. If the information falls into this category, you may attest that you are using this exemption by signing below.

____________________, ________________
Signature Date

**EXEMPTION II**
If your information pertains exclusively to the release of scientific data, *i.e.* data pertaining to studies of clouds, soil, vegetation, oceans, and planets, without the disclosure of information pertaining to articles controlled by the ITAR or EAR, such as flight instruments, high speed computers, or launch vehicles, the information is exempt from further review. If the information falls into this category, you may attest that you are using this exemption by signing below.

Keith Olson, 3/16/00
Signature Date

**EXEMPTION III**
If your information falls into the areas of concern as referenced above, but is offered at a general purpose or high level, *i.e.* poster briefs and overviews, where no specific information pertaining to ITAR or EAR controlled items is offered, the information is exempt from further review. If the information falls into this category, you may attest that you are using this exemption by signing below.

____________________, ________________
Signature Date

**EXEMPTION IV**

If your information is not satisfied by the 3 exemptions stated above, the information may be released using exemption 125.4(b)(13) of the ITAR. Use of this exemption is afforded only to agencies of the Federal Government and allows the release of ITAR controlled information into the public domain. But the GSFC Export Control Office has determined that use of this exemption will be allowed only after we receive assurance that such release is a responsible action. To this end, an internal guideline has been established pursuant to the use of this exemption: That the information does not offer specific insight into design, design methodology, or design processes of an identified ITAR controlled item in sufficient detail (by itself or in conjunction with other publications) to allow a potential adversary to replicate, exploit and/or defeat controlled U.S. technologies. All signatures of approval on NASA Form 1676 expressly indicate concurrence with the responsible use of Exemption IV when Exemption IV has been cited by the author. If you determine that you have met this criteria, you may attest your determination by signing below, and the GSFC Export Control Office will offer favorable consideration toward approving your presentation/publication request under this special exemption.

____________________, ________________
Signature Date

If you do not satisfy the above exemptions, please contact the GSFC Export Control Office for further clarification on the releasability of your information under the ITAR or EAR.